CVEL

THE CLEMSON UNIVERSITY VEHICULAR ELECTRONICS LABORATORY

TECHNICAL REPORT: CVEL-14-058.1

Decomposition of Shielding Effectiveness into Absorption and Reflection Components

Andrew J. McDowell and Dr. Todd Hubing

Clemson University

October 12, 2016

This is a minor revision of CVEL-14-058 dated April 10, 2014.
The revised report corrects an error in the plot shown in Fig. 3.

Table of Contents

Abstract

Plane wave shielding effectiveness is frequently expressed as the sum of three terms called penetration loss, reflection loss, and an internal reflections correction term. This well-known decomposition was originally developed by Schelkunoff, and provides an intuitive way of relating material properties to the overall shielding effectiveness of certain shielding materials, especially metallic materials. In experimentally characterizing the shielding effectiveness of composite materials, other methods of describing the reflection and absorption contributions to shielding are commonly used. These other decompositions are generally more closely related to the reflected and absorbed power densities and are thus easier to obtain from measurements. This paper analyzes different decompositions that have been used to describe the shielding properties of materials. It introduces the term mismatch decomposition to describe a method for decomposing shielding effectiveness into terms related to the reflectance and absorptance of a material. This decomposition method has been effectively applied by a number of researchers, but inconsistent terminology has prevented the full value of this decomposition from being recognized. The mismatch decomposition results in terms that are useful as figures of merit because they are closely related to the reflected and absorbed power and are readily derived from standard measurements of plane wave shielding effectiveness.

1. Introduction

Electromagnetic shielding plays an important role in ensuring the electromagnetic compatibility (EMC) of many electronic systems. Shields have traditionally been constructed from metals and metal coatings, but this approach to shielding can be expensive and/or heavy [1]. The need for lightweight and inexpensive shielding materials has driven a large amount of research in recent years on the shielding properties of polymer composites and intrinsically conductive polymers [2]–[19]. Additionally, it is often desirable for a shield to absorb a large amount of energy relative to the energy that it reflects so that secondary electromagnetic pollution is minimized [3], [5], [8], [20]–[22]. Thus quantifying the reflection and absorption contributions to shielding is important in many applications.

The shielding properties of materials are typically quantified by measuring the electromagnetic shielding effectiveness (EMSE) of a flat material sample with a given thickness. The EMSE is the insertion loss expressed in decibels of the sample in free space with a normally incident plane wave. In recent books on EMC (for example [23]–[28]), plane wave shielding is typically presented in a model known as the transmission line model of shielding. This model of shielding was originally developed by Schelkunoff [29]–[31]. Schelkunoff analyzed the EMSE of planar, cylindrical, and spherical shields by using wave impedances in a manner analogous to transmission line characteristic impedances. He applied the transmission line concepts of reflection and transmission coefficients to the shielding analysis. The transmission line model of shielding gives an exact solution for the EMSE of an infinite homogeneous material sheet or layers of sheets with a normally-incident plane wave. However, the transmission line model of shielding gives only approximate solutions in situations with non-plane waves, for example a near field source next to a planar shield, or the cylindrical and spherical shields that Schelkunoff analyzed. For approximate application of the transmission line model to situations with non-plane waves, the wave impedance must be selected carefully to achieve good accuracy [28], [32]–[34]. The transmission line model of shielding is also applicable to composite materials using effective constitutive parameters when the heterogeneities are evenly dispersed and are small compared to the effective wavelength in the medium [35]. Section 2 of this paper reviews the transmission line model of shielding.

The transmission line model of shielding breaks up the decibel value of EMSE into the sum of three decibel loss terms: penetration loss (also called absorption loss), reflection loss, and an internal reflections correction term (also called multiple reflections loss) as illustrated in (1).

$$\mathrm{SE} = \overbrace{\underbrace{A}_{\substack{\text{Penetration loss /}\\ \text{absorption loss}}} + \underbrace{R}_{\text{Reflection loss}} + \underbrace{B}_{\substack{\text{Internal reflections}\\ \text{correction term}}}}^{\text{Schelkunoff decomposition (terms in dB)}} \tag{1}$$

This decomposition of EMSE will be referred to in this paper as the *Schelkunoff decomposition*. Additionally, the sum of reflection loss and the internal reflections correction term will be referred to in this paper as the *net reflection loss*. The internal reflections correction term is generally negligible for thick good conductors; but for poor conductors, thin metallic films, or shielding at low frequencies, it can have a large negative value. In EMC textbooks, graphs of the EMSE of materials decomposed into the terms of the Schelkunoff decomposition are commonly presented. Although the Schelkunoff decomposition may break EMSE into components that are easy to calculate and intuitive for understanding the parametric dependence of EMSE, the terms do not represent very useful figures of merit and they do not correlate to quantities obtained from shielding effectiveness measurements in a straightforward manner. Section 3 of this paper reviews and analyzes the Schelkunoff decomposition, its physical interpretations, and its mathematical relationship to network parameters and reflectance/absorptance.

Even though the terms describing reflection and absorption in the Schelkunoff decomposition are not closely related to the actual levels of reflected and absorbed power, terms from the Schelkunoff decomposition have been used to quantify the reflection and absorption contributions to EMSE in some experiments on materials (for example [3], [5]). However, other measures have also been used to quantify the reflection and absorption contributions to shielding. For the analysis of radar absorbing materials, it is common to use the reflection coefficient expressed in decibels with the absorbing material backed by a thick metal sheet approximating a perfect electrical conductor as a specification of the balance of reflection/absorption [3], [36]. A number of recent papers have used the input reflection coefficient expressed in decibels to quantify reflected power in shielding experiments [18], [37]. Of course, one could use the linear measures of reflectance (reflected power density divided by incident power density), transmittance (transmitted power density divided by incident power density), and absorptance (absorbed power density divided by incident power density) to describe how much of a material's shielding is due to reflection and how much is due to absorption. Such measures are employed in a number of recent shielding experiments [10], [38], [39]. However, it is often desired to have decibel measures of reflection and absorption that sum to give the total decibel EMSE as the terms in the Schelkunoff decomposition do.

In transmission line engineering, a quantity called the *mismatch loss* is frequently used to describe the degree of mismatch in a transmission line at a particular point. Mismatch loss has been widely used in the analysis of the shielding properties of composites in recent publications [6], [17], [20], [21], [40]–[45]; although the authors of these publications used different terminology to describe this loss. Mismatch loss is a different quantity than the reflection loss or net reflection loss of the Schelkunoff decomposition. This point is explicitly made in a few of these publications, but confusion arises from the fact that the decomposition based on mismatch loss is often described using the same name or notation as the terms in the Schelkunoff decomposition. Some recent publications incorrectly imply that the mismatch loss is an approximation for the Schelkunoff reflection loss for good conductors when the internal reflections correction term is close to zero (for example [21], [43], [45]). The decomposition of EMSE using mismatch loss and another term called dissipation loss will be referred to in this paper as the *mismatch decomposition*. The mismatch decomposition gives terms that are useful as figures of merit because they are closely related to the absorbed and reflected power. Furthermore, the mismatch decomposition may be interpreted as a comparison to a situation of conjugate matching between the source impedance and the equivalent input or output impedance of the shield transmission line analog terminated with free space. Section 4 of this paper reviews and analyzes the mismatch decomposition and compares it to the Schelkunoff decomposition.

Section 5 of this paper provides graphical plots of various EMSE decompositions computed for three example shields and Section 6 concludes the paper. Additionally, the appendix (referenced in Section 3) shows how the Schelkunoff decomposition can be generalized using image parameters to apply to layered materials.

2. Review of Transmission Line Model of Shielding

The basis for the transmission line (TL) model of shielding is that the voltage in a TL is analogous to the electric field intensity of a plane wave and the current in a TL is analogous to the magnetic field intensity of a plane wave. Additionally the distributed series inductance per unit length, shunt capacitance per unit length, and shunt conductance per unit length of a TL are analogous to the respective constitutive parameters of permeability, permittivity, and conductivity. These analogies make most TL concepts directly applicable to the analysis of shielding of normally incident plane waves.

Fig. 1 shows a depiction of the basic plane wave shielding problem of a single-layered homogeneous and isotropic material that is infinite in the *xy*-plane but has thickness t in the z direction. The shield is surrounded by free space with intrinsic impedance η_0 and propagation constant γ_0 on either side for $z < 0$ and $z > t$. For the electric and magnetic field intensity vectors expressed as RMS phasors, the complex Poynting vector is given by $\mathbf{S} = \mathbf{E} \times \mathbf{H}^*$ and the time-average Poynting vector is Re($\mathbf{S}$). By the nature of a plane wave, the electric and magnetic field vectors are spatially orthogonal, so the cross product of vectors reduces to a multiplication of scalars. The magnitude of the time-average Poynting vector is the time-average power density (with units of watts per square meter). Because η_0 is real, the time-average power densities associated with the incident, reflected, and transmitted fields in Fig. 1 are given by: $P_I = |E_I|^2/\eta_0$, $P_R = |E_R|^2/\eta_0$, and $P_T = |E_T|^2/\eta_0$, respectively. By conservation of energy,

$$P_I = P_R + P_T + P_A, \tag{2}$$

where P_I is the incident power density, P_R is the reflected power density, P_T is the transmitted power density, and P_A is the absorbed power density. It is more convenient, however, to consider power densities normalized to the incident power density. Dividing each term in (2) by P_I gives the normalized power balance equation,

$$1 = \hat{P}_R + \hat{P}_T + \hat{P}_A. \tag{3}$$

The following notation and terminology for these power densities normalized to the incident power density will be used in this paper: $\hat{P}_R$ is called the reflectance, $\hat{P}_T$ is called the transmittance, and $\hat{P}_A$ is called the absorptance.

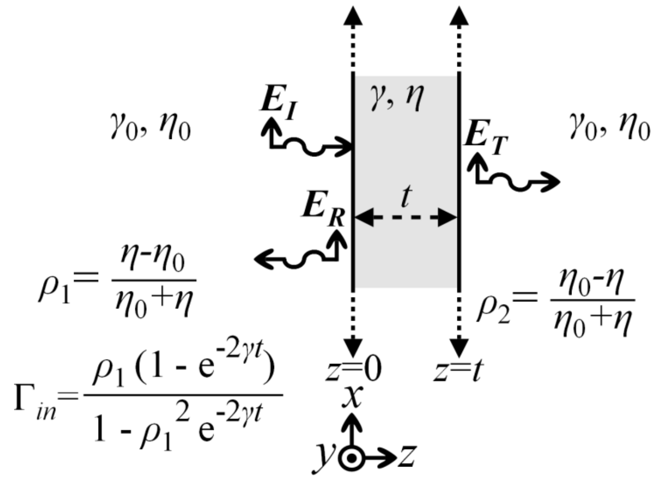

Fig. 1. Basic plane wave shielding problem of homogeneous and isotropic material infinite in *xy*-plane.

With the permeability μ, the conductivity σ, and the permittivity ϵ potentially expressed as complex numbers and with ω representing the angular frequency of the wave, the propagation constant in the material is:

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} \,. \tag{4}$$

As in (4), the propagation constant may be written in terms of the attenuation constant α and the phase constant β. The intrinsic impedance of the material is:

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \,. \tag{5}$$

Another term important for the analysis of shielding materials is the skin depth, which is defined as $\delta_s = 1/\alpha$. In good conductors when the frequency is such that $\sigma \gg \omega\epsilon$, the intrinsic impedance may be approximated as $\eta \approx \sqrt{j\omega\mu / \sigma}$ and the propagation constant may be approximated as $\gamma \approx \sqrt{\omega\mu\sigma}\left(1+j\right)/\sqrt{2}$. Thus the skin depth in good conductors can be closely approximated by $\delta_s \approx \left(\pi f \mu\sigma\right)^{-1/2}$, where $f = \omega/(2\pi)$. Elementary electric field reflection coefficients are denoted by ρ and represent the ratio of reflected to incident electric field intensity that would occur at the junction of two materials if both materials were infinitely thick. Actual reflection coefficients representing the ratio of electric field intensity in the backward and forward traveling waves next to a junction are denoted by Γ. The elementary electric field reflection and transmission coefficients of a normally incident plane wave traveling from free space and impinging on the material in Fig. 1 are given by $\rho_1 = \left(\eta - \eta_0\right)/\left(\eta + \eta_0\right)$ and $T_1 = 2\eta / \left(\eta + \eta_0\right)$, respectively. Likewise, the electric field reflection and transmission coefficients of a wave traveling out of the material and into free space are given by $\rho_2 = \left(\eta_0 - \eta\right)/\left(\eta + \eta_0\right)$ and $T_2 = 2\eta_0 / \left(\eta + \eta_0\right)$, respectively. The relationships $T_1 = 1 + \rho_1$, $T_2 = 1 + \rho_2$, and $\rho_1 = -\rho_2$ will be used for subsequent derivations in this paper.

The transmitted electric field can be expressed as a sum of the field that would be transmitted directly through the material, $E_I T_1 e^{-\gamma t} T_2$, and the fields that experience internal partial reflections an even number of times and then are transmitted into the region $z > t$ of Fig. 1. Thus, the transmitted electric field intensity can be expressed as the following summation of partial reflections:

$$E_T = E_I T_1 e^{-\gamma t} \sum_{m=0}^{\infty} \left(-\rho_1 \rho_2 e^{-2\gamma t}\right)^m T_2 . \tag{6}$$

By converting the electric field intensities represented in (6) to power densities, using the formula for the sum of a convergent geometric series, noting that $\rho_1^2 = -\rho_1 \rho_2$, and dividing by the incident power density, the transmittance can be expressed as,

$$\hat{P}_T = \frac{P_T}{P_I} = \left| \frac{T_1 T_2 e^{-\gamma t}}{1 - \rho_1^2 e^{-2\gamma t}} \right|^2 . \tag{7}$$

The reflectance is easily found by calculating the input reflection coefficient and taking the magnitude squared of this value:

$$\hat{P}_R = \left|\Gamma_{in}\right|^2 = \left| \frac{\rho_1 \left(1 - e^{-2\gamma t}\right)}{1 - \rho_1^2 e^{-2\gamma t}} \right|^2 . \tag{8}$$

Consequently, from the power balance relationship, (3), the absorptance can be expressed as,

$$\hat{P}_A = 1 - \hat{P}_T - \hat{P}_R . \tag{9}$$

3. Schelkunoff Decomposition of Shielding Effectiveness

In general, EMSE can be defined as either the electric or magnetic field insertion loss expressed in decibels when the material is added [26]. However, for the plane wave shielding problem shown in Fig. 1, this is equivalent to the power insertion loss or simply the reciprocal of the transmittance expressed in decibels:

$$\mathrm{SE} = -10 \log_{10}\left(\hat{P}_T\right) = -20 \log_{10} \left| \frac{T_1 T_2 e^{-\gamma t}}{1 - \rho_1^2 e^{-2\gamma t}} \right| . \tag{10}$$

In the EMC literature, there is widespread decomposition of (10) into decibel quantities called penetration loss, reflection loss, and the internal reflections correction term that sum to give the EMSE. As described in Section 1, this decomposition is called the Schelkunoff decomposition and can be expressed as,

$$\mathrm{SE} = A + R + B . \tag{11}$$

The penetration loss, which is also called absorption loss, is the reciprocal of the attenuation that occurs when a wave travels through the material once and is the non-negative quantity given by:

$$A = -20 \log_{10} \left| e^{-\gamma t} \right| = 20 \log_{10}(e) \cdot \alpha t \approx 8.7 \alpha t . \tag{12}$$

The penetration loss can equivalently be physically interpreted as the ratio expressed in decibels of the magnitude of the incident complex Poynting vector to the magnitude of the transmitted complex Poynting vector when the shield is simultaneously matched for no reflection on both sides.

The reflection loss is the reciprocal of the product of the transmission coefficients at both interfaces expressed in decibels and represents the reduction in transmitted field that would occur due to reflections off of both interfaces in the absence of loss in the medium and internal reflections between the two interfaces. Reflection loss is the non-negative quantity given by:

$$R = -20\log_{10}\left|T_1T_2\right| = -20\log_{10}\left|1-\rho_1^2\right|. \tag{13}$$

The remainder of the expression for EMSE is the correction term for multiple internal reflections, accounting for the reflections represented by the geometric series in (6). The internal reflections correction term, which is also called the multiple reflections loss, is given by:

$$B = 20\log_{10}\left|1-\rho_1^2 e^{-2\gamma t}\right|. \tag{14}$$

Because $\left|\rho_1\right| < 1$, it follows that the upper positive limit of B is about $3\,\text{dB}$ which occurs when $\rho_1{}^2 e^{-2\gamma t} = \pm j$. For sufficiently thick good conductors at frequencies where $t \gg \delta_S$, the argument of the absolute value function in (14) is near unity and $B \approx 0\,\text{dB}$.

The sum of the internal reflections correction term and the reflection loss will be called the net reflection loss in this paper:

$$R_{net} = R + B. \tag{15}$$

This net reflection loss thus represents a comparison loss comparing the magnitude of the ratio of the incident and transmitted complex Poynting vectors of the actual shield configuration to the corresponding ratio which would occur if the shield was simultaneously matched.

3.1 Determining Decomposition from Scattering Parameters

There are many different techniques that have been used to obtain measurements approximating plane wave EMSE. Often these measurement techniques make use of transverse electromagnetic (TEM) cells or coaxial airlines. Analysis of these different measurement techniques is beyond the scope of this paper, but if one obtains the necessary complex-valued scattering parameters S_{11} and S_{21} of a single-layered shield in free space, the terms of the Schelkunoff decomposition can easily be obtained. As presented in [46], the elementary reflection coefficient of a wave impinging on the material can be found by,

$$\rho_1 = \chi \pm \sqrt{\chi^2 - 1}, \tag{16}$$

where the solution giving $\left|\rho_1\right| \le 1$ is taken and where,

$$\chi = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}. \tag{17}$$

From this result, the propagation term can be determined as,

$$e^{-\gamma t} = \frac{S_{11} + S_{21} - \rho_1}{1 - \left(S_{11} + S_{21}\right)\rho_1}. \tag{18}$$

Then, the penetration loss, the reflection loss, and the internal reflections corrections term can be found from the results of (16) and (18) using the formulas in (12), (13), and (14).

3.2 Determining Power Distribution from Decomposition

The full characterization of a reciprocal linear two-port network requires six real-valued parameters, while a network known to be symmetric may be characterized by four real-valued parameters. Thus, the three real-valued parameters that are given by the Schelkunoff decomposition are by themselves insufficient to fully characterize a network. However, it is often of interest to know simply how much power is reflected and absorbed by a shield. This raises the question of whether it is possible to determine the reflectance/absorptance from the Schelkunoff decomposition of a single-layered shield in different circumstances.

3.2.1 Good Conductor Approximation

It is easy to approximate the reflectance/absorptance from the Schelkunoff decomposition of a shield composed of a good conductor at frequencies when $\sigma \gg \omega\epsilon$. For good conductors, the magnitude of η is generally very small at frequencies of interest for EMC. For example, the intrinsic impedance of copper at 1 GHz is $0.0037\angle 45°\ \Omega$ and $|\eta|$ is even lower for $f < 1$ GHz. Additionally, both the propagation constant and intrinsic impedance in good conductors have approximately equal real and imaginary parts. These relationships are evident from the following equation which is valid for materials with real-valued permeability and conductivity:

$$\frac{\mathrm{Re}(\eta)^2}{\mathrm{Im}(\eta)^2} = \frac{\sqrt{1+\tan^2\delta}+1}{\sqrt{1+\tan^2\delta}-1} = \frac{\beta^2}{\alpha^2}, \tag{19}$$

where $\tan\delta = (\omega\epsilon'' + \sigma)/(\omega\epsilon')$ is the loss tangent (which is very large for good conductors) and where the complex permittivity is expressed as $\epsilon = \epsilon' - j\epsilon''$.

Thus the normalized intrinsic impedance (which is denoted by ζ with real part ζ_r) can be approximated as,

$$\zeta = \eta/\eta_0 \approx \zeta_r(1+j). \tag{20}$$

With this approximation, the argument of the logarithm in the reflection loss term (which is denoted by M_R) can be expanded as,

$$M_R = 10^{-R/10} = \left|\frac{4\zeta}{(\zeta+1)^2}\right|^2 \approx \frac{32\zeta_r^2}{4\zeta_r^4 + 8\zeta_r^3 + 8\zeta_r^2 + 4\zeta_r + 1}. \tag{21}$$

Solving (21) for ζ_r and selecting the correct root (the one giving $0 < \zeta_r < 1$ for the possible interval of $0 < M_R \le 1$ gives,

$$\zeta_r \approx \frac{1}{2\sqrt{M_R}}\left(-\sqrt{M_R} - \sqrt{-4\sqrt{2}\sqrt{M_R} - M_R + 8} + 2\sqrt{2}\right). \tag{22}$$

Then, the elementary electric field reflection coefficient may be approximated as,

$$\rho_1 \approx \frac{\zeta_r(1+j)-1}{\zeta_r(1+j)+1}. \tag{23}$$

From (12), the product of the attenuation constant and thickness may be written in terms of the Schelkunoff absorption loss as, $\alpha t = A/(20\log_{10}(e))$. The product of the propagation constant and thickness may thus be approximated as,

$$\gamma t \approx \alpha t(1+j). \tag{24}$$

Also note that the denominator of (8) is $10^{B/10}$. Thus the reflectance can be approximated by substituting $10^{B/10}$, γt from (24), and ρ_1 from (23) into (8). The transmittance is $\hat{P}_T = 10^{-\mathrm{SE}/10}$, so the absorptance can be approximated with (9). These approximations are shown to be accurate for a variety of example materials later in this paper.

3.2.2 General Material Solution

For a general single-layered material for which it is only known that the relative permeability is one, but for which it is not necessarily the case that $\sigma \gg \omega\epsilon$, determining the reflectance/absorptance from the Schelkunoff decomposition is a more involved process. For such a material, we can write the intrinsic impedance as $\eta = j\omega\mu_0 / \gamma = j\omega\mu_0 / \left(\alpha + j\beta\right)$. By expressing the reflection coefficient ρ_1 in terms of η_0, ω, α, and β, we can write the arguments of the logarithms in the Schelkunoff decomposition reflection loss and internal reflections correction terms as the following two expressions, which both involve entirely real-valued quantities:

$$10^{-R/10} = \frac{16\eta_0^2 {\mu_0}^2 \omega^2 \left(\alpha^2 + \beta^2\right)}{\left(\eta_0^2 \left(\alpha^2 + \beta^2\right) + 2\beta\eta_0\mu_0\omega + {\mu_0}^2\omega^2\right)^2} \text{ and} \quad (25)$$

$$10^{-B/10} = f(\alpha, \beta, \mathrm{e}^{2\alpha t}, \cos(2\beta t), \sin(2\beta t), \eta_0, \mu_0, \omega), \quad (26)$$

where f is a real-valued multivariate rational function.

A nonlinear system of two equations with two unknowns in terms of α and β is formed by (25) and (26) with the symbolic substitution made in (26) that $t = A/(20 \log_{10}(e) \cdot \alpha)$. Although this system is solvable with numerical methods, the robustness of this procedure was not thoroughly investigated as these formulas are intended primarily to indicate the theoretical relationships between the Schelkunoff decomposition and the reflectance/absorptance; furthermore, the approximate method in the previous section works well for many practical shielding materials. This procedure may be simplified to a closed form solution of (25) expanded in terms of β as a quartic polynomial if the thickness is also known. Once α and β are obtained, the reflectance and absorptance are easily computed.

3.3 Application to Layered Shields

Schulz presented an extension of the Schelkunoff decomposition to layered shields in [47]. Schulz's extension to the Schelkunoff decomposition is briefly reviewed here. The field solution for the general multilayered (with homogeneous and isotropic layers) plane wave shielding problem is presented in Fig. 2 below.

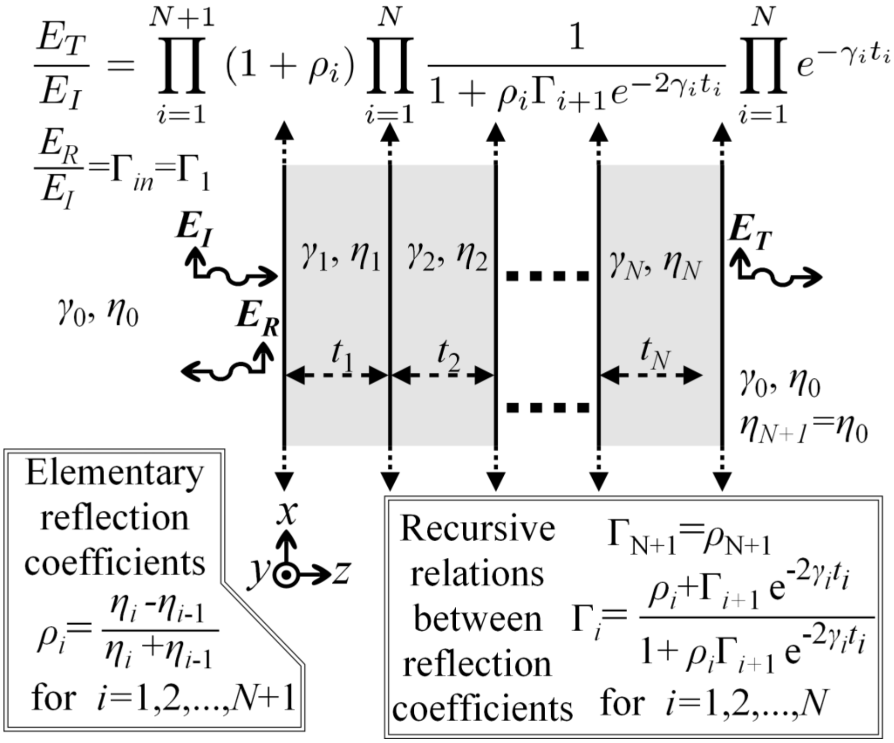

Fig. 2. Field solution for multi-layered plane-wave shielding problem.

From the field solution (using the notation in Fig. 2), Schulz defines the penetration loss as,

$$A = -20\log_{10}\left|\prod_{i=1}^{N} e^{-\gamma_i t_i}\right|, \tag{27}$$

the reflection loss as,

$$R = -20\log_{10}\left|\prod_{i=1}^{N+1}\left(1+\rho_i\right)\right|, \tag{28}$$

and the internal reflections correction term as,

$$B = 20\log_{10}\left|\prod_{i=1}^{N}\left(1+\rho_i\Gamma_{i+1}e^{-2\gamma_i t_i}\right)\right|. \tag{29}$$

If, however, one were to apply the procedure presented previously for obtaining the Schelkunoff decomposition of a single layered shield to a symmetrically layered shield, one would generally obtain a different decomposition as illustrated in Fig. 3 below. In this figure, “Image A_m” and “Image $R_{m,net}$” represent what one would obtain for A and R_{net}, respectively, by applying the previously presented procedure for obtaining the Schelkunoff decomposition from scattering parameters. The trace labeled “Schulz R_{net}” represents the sum of (28) and (29) for this shield and the trace labeled “Schulz A” is found from (27).

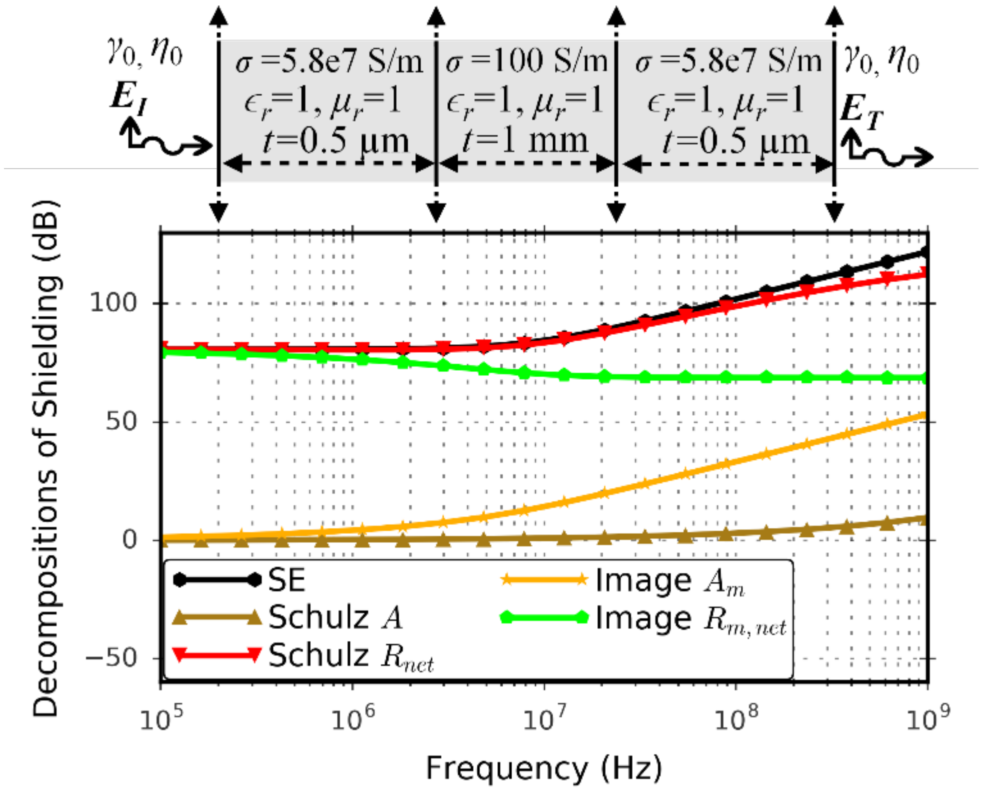

Fig. 3. Comparison of Schulz's generalization of Schelkunoff decomposition to the decomposition which would be obtained if the shield was treated like a single-layered shield and the procedure in section 3.1 was used (these terms are prefixed by the word "Image.")

The decomposition corresponding to the curves prefixed by the word "Image" in Fig. 2 is what one would obtain using image parameters to generalize the comparison loss interpretations of the single layered shield for layered media. This generalization of the Schelkunoff decomposition using image parameters is presented in the appendix. However, this image parameter generalization is only useful from a theoretical point of view because not only do its terms lack usefulness as practical figures of merit (like the Schelkunoff decomposition and Schulz's extension), but its terms are not useful as intermediate terms in calculating EMSE (unlike the Schelkunoff decomposition and Schulz's extension which are useful in this respect). The theoretically interesting thing about this image parameter decomposition is that its terms can be interpreted by comparing to a hypothetical situation of simultaneous image matching (a generalization of the reflectionless matched condition) of the Schelkunoff decomposition. Specifically, the image absorption loss is the ratio expressed in decibels of the magnitudes of the incident and transmitted complex Poynting vectors when the shield is image matched.

4. Mismatch Decomposition

4.1 Basic Description

A number of authors have used a decomposition, commonly used in the analysis of mismatches between transmission lines for the decomposition of experimental shielding effectiveness measurements [6], [17], [20], [21], [40]–[45]. In these papers, the decomposition terms have been called experimental reflection / absorption losses [20], net shielding by reflection / absorption [40], [41], and various other names. Here the terms will be called *mismatch loss* and *dissipation loss* to be consistent with the terminology that has been used for decades in the analysis of transmission lines

[48], [49]. The decomposition is called the *mismatch decomposition* here, because it is based on a comparison to conjugate matching of the equivalent input or output impedance of a network.

Mismatch loss, which is also called conjugate mismatch loss, is defined at a reference plane between a source and a load as the ratio of the power that would be delivered to a conjugate-matched load to the power delivered to the mismatched load. In other words, it is the ratio expressed in decibels of the power available from the source to the power delivered to the load. Note that mismatch loss is only defined at a reference plane between a load and a source. The mismatch loss at the input of a transmission line segment that is mismatched at both ends, however, can be defined as the mismatch loss between the source and the equivalent input impedance of the transmission line [50]. Alternatively, it can be defined at the output of the transmission line segment by taking the Thévenin equivalent of the source cascaded with the transmission line.

The mismatch loss at the input-side of a shield in free space may be expressed as:

$$L_M = 10\log_{10}\left(\frac{\left|\eta_0+\eta_{in}\right|^2}{4\operatorname{Re}(\eta_0)\operatorname{Re}(\eta_{in})}\right), \tag{30}$$

where η_{in} is equivalent wave impedance looking into the transmission line analog of the shield terminated with η_0:

$$\eta_{in} = \eta_0\left(1+\Gamma_{in}\right)/\left(1-\Gamma_{in}\right). \tag{31}$$

Because η_0 is real, mismatch loss can also be expressed as:

$$L_M = -10\log_{10}\left(1-\hat{P}_R\right). \tag{32}$$

The efficiency of a transmission line section is defined as the power delivered to the load divided by the net power input. Application of this concept to the transmission line analogy of shielding gives the efficiency as,

$$h = \frac{P_T}{P_I - P_R} = \frac{\hat{P}_T}{1-\hat{P}_R}\ . \tag{33}$$

The dissipation loss of the shield is then defined as the reciprocal of the efficiency expressed in decibels:

$$L_D = -10\log_{10}(h). \tag{34}$$

Note that the mismatch loss (32) and the dissipation loss (34) add up to the total EMSE:

$$\mathrm{SE} = L_D + L_M\,. \tag{35}$$

Another way of viewing the dissipation loss is to define the effective absorptance as the absorbed power relative to the power not reflected,

$$\hat{P}_{A,eff} = \hat{P}_A/\left(1-\hat{P}_R\right). \tag{36}$$

Then the dissipation loss can be expressed as,

$$L_D = -10\log_{10}\left(1-\hat{P}_{A,eff}\right). \tag{37}$$

4.2 Comparison to Schelkunoff Decomposition

From the equivalence of (30) and (32), it is apparent that mismatch loss has an advantage over the Schelkunoff decomposition in that mismatch loss is closely related to the power balance as well as the impedance mismatch. Thus it is trivial and intuitive to obtain the decomposition from measured network parameters and to obtain the reflectance/absorbance from the decomposition. Another advantage of this decomposition is that the terms in this decomposition have the same physical meaning as comparison losses for single-layered and multi-layered materials. In contrast, the Schelkunoff decomposition generalized for layered materials by Schulz lacks this property. Although the image parameter generalization of the Schelkunoff decomposition presented in the appendix does yield identical comparison loss interpretations for single and multi-layered shields, its terms are neither useful as figures of merit nor as intermediate calculation terms.

One disadvantage of the mismatch decomposition is that the terms in the mismatch decomposition are less useful for understanding the parametric dependence of EMSE; however, the terms are intuitively simple and represent useful figures of merit. The mismatch loss decreases with the power that is either absorbed by the shield or transmitted through the shield and the dissipation loss gives a measure of the absorbed power relative to the power not reflected. Authors who have used the terms of this decomposition as figures of merit have justified its use because increasing the percentage of conductive nanoparticles in a composite increases the reflectance of the material. Thus the absorptance will decrease simply because there is less power available to be absorbed. Therefore, these authors argue that for purposes of describing shielding mechanisms, the measure of absorption should be of the absorbed power relative to the power not reflected [41].

Mismatch loss and dissipation loss are totally different quantities than the terms in the Schelkunoff decomposition, even for good conductors. However, a number of recent papers are unclear in this regard (for example [20], [21], [40], [41], [43], [45]). The Schelkunoff reflection loss can be expressed as,

$$R = -10\log_{10}\left(1 - 2\mathrm{Re}(\rho_1^2) + \left|\rho_1^2\right|^2\right). \tag{38}$$

The elementary electric field reflection coefficient between free space and a good conductor only has a very small imaginary part so it follows that $\mathrm{Re}(\rho_1^2) \approx |\rho_1^2|$. Thus the Schelkunoff reflection loss can roughly be approximated as,

$$R \approx -10\log_{10}\left(1 - \left|\rho_1\right|^2\right)^2 = -20\log_{10}\left(1 - \left|\rho_1\right|^2\right). \tag{39}$$

For thick good conductors with $t \gg \delta_s$, the reflectance given by (8) may also be approximated as, $\hat{P}_R \approx |\rho_1|^2$, since $e^{-2\gamma t}$ is very small. Thus, the mismatch loss can be approximated as,

$$L_M \approx -10\log_{10}\left(1 - \left|\rho_1\right|^2\right). \tag{40}$$

Notice that the mismatch loss approximated by (40) is half of the decibel value of the Schelkunoff decomposition reflection loss approximated by (39) for materials in which $t \gg \delta_s$ and $\sigma \gg \omega\epsilon$. Consequently, the dissipation loss will be greater than the Schelkunoff absorption loss for thick good conductors.

5. Examples

The calculated EMSE decompositions are shown in Fig. 4–Fig. 6 for three different materials. In these plots, A, R, B, and R_{net} represent the absorption loss, reflection loss, internal reflections correction term and net reflection loss of the Schelkunoff decomposition, respectively. L_M and L_D represent the mismatch loss and dissipation loss of the mismatch decomposition, respectively. Finally, an additional decomposition consisting of three decibel power ratios is provided that illustrates another possible way to describe the reflection and absorption contributions to shielding. These three decibel ratios also sum to give the total EMSE. The first of these additional decibel ratios, shown in magenta in the figures, is the ratio of reflected to absorbed power, $10\log_{10}(\hat{P}_R / \hat{P}_A)$. Next, shown in gray, is the decibel ratio of absorbed to transmitted power, $10\log_{10}(\hat{P}_A / \hat{P}_T)$. The last of these ratios, shown in cyan, is the decibel ratio of incident to reflected power or the return loss, $10\log_{10}(1/\hat{P}_R)$.

In all of the plots, note that the Schelkunoff net reflection loss is greater than the mismatch loss. Also, while the reflected power is greater than the absorbed power for all of these examples, the Schelkunoff absorption loss exceeds the Schelkunoff net reflection loss for the cases in Fig. 4 and Fig. 6 above several GHz. In each of these examples, the dissipation loss exceeds the mismatch loss. For the examples in Fig. 5 and Fig. 6, the internal reflections correction term of the Schelkunoff decomposition has a negative value of relatively large magnitude at frequencies up to hundreds of megahertz.

Note that the decibel ratio of absorbed to transmitted power approximates the dissipation loss and the decibel ratio of reflected to absorbed power approximates the mismatch loss for all of the examples. In Fig. 4, these approximations hold to within 0.0012 dB. In Fig. 5, these approximations hold to within 0.083 dB. Finally, in Fig. 6, the mismatch loss differs from the decibel ratio of reflected power to absorbed power by up to 2.67 dB and the dissipation loss differs from the ratio of absorbed to transmitted power by up to 0.37 dB. In general, the dissipation loss will approximately equal the decibel absorbed-to-transmitted power ratio when the power absorbed is much greater than the power transmitted as is evident from rewriting the formula for dissipation loss as,

$$L_D = 10\log_{10}\left(\hat{P}_A / \hat{P}_T + 1\right). \tag{41}$$

Thus if the absorbed-to-transmitted power ratio exceeds 10 dB, then this ratio will be within 0.5 dB of the dissipation loss. Likewise, the mismatch loss can be written in the following form,

$$L_M = 10\log_{10}\left(\hat{P}_R / (\hat{P}_A + \hat{P}_T) + 1\right), \tag{42}$$

which illustrates why it is approximately equal to the decibel ratio of reflected to absorbed power in the examples.

Additionally, the errors associated with approximating the absorptance and reflectance using the good conductor approximation-based equations in (21)−(24) were investigated. In Fig. 4, the approximated absorptance was within 0.0022% of the actual absorptance from 1 MHz to 10 GHz. For Fig. 5, the approximated absorptance was within 0.0532% of the actual absorptance from 1 MHz to 10 GHz. Finally, in Fig. 6 the approximated absorptance was within 3.64% of the actual absorptance from 1 MHz to 10 GHz and within 1.02% from 1 MHz to 1 GHz. The maximum approximation errors for the reflectance were lower than those for the absorptance for each of the three examples.

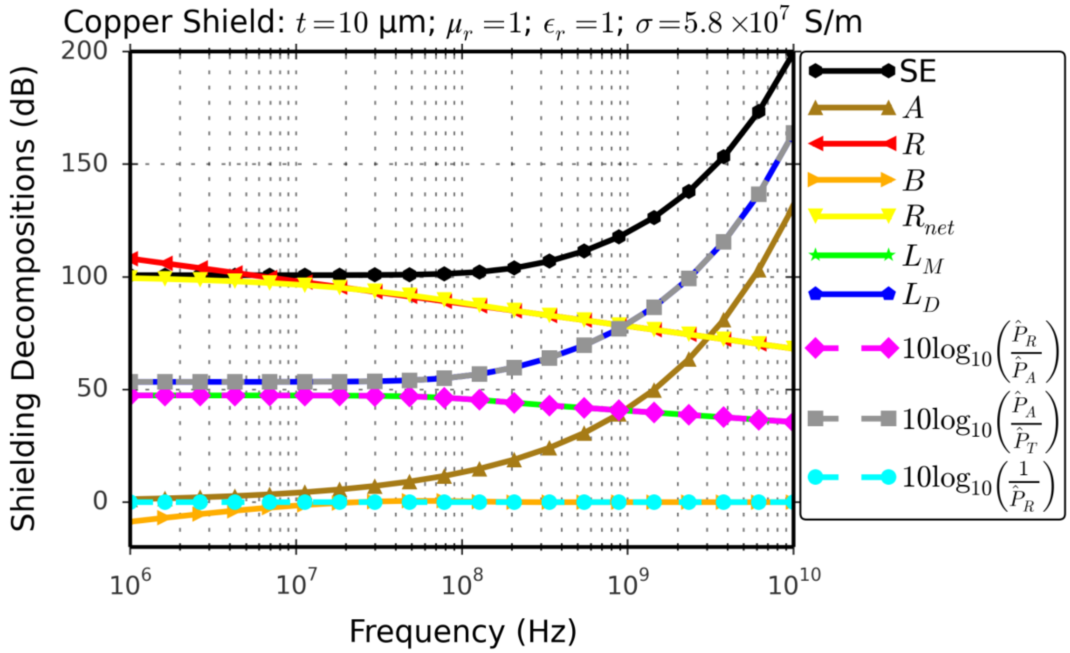

Fig. 4. Shielding decompositions for 10 μm thick copper shield.

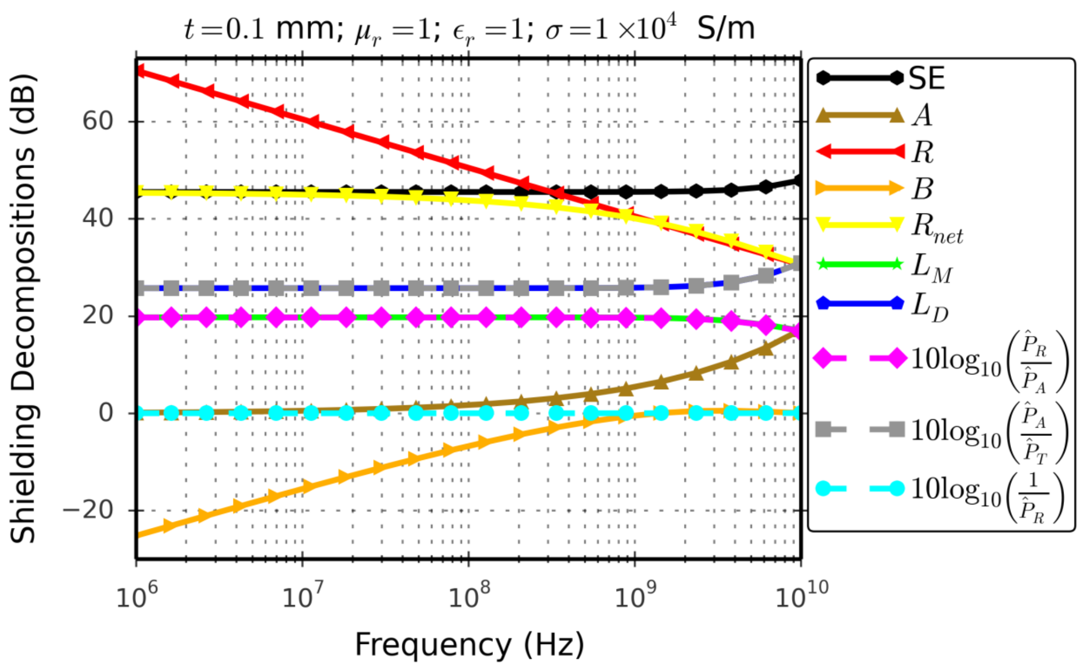

Fig. 5. Shielding decompositions for 0.1 mm-thick shield with σ = 1×104 S/m.

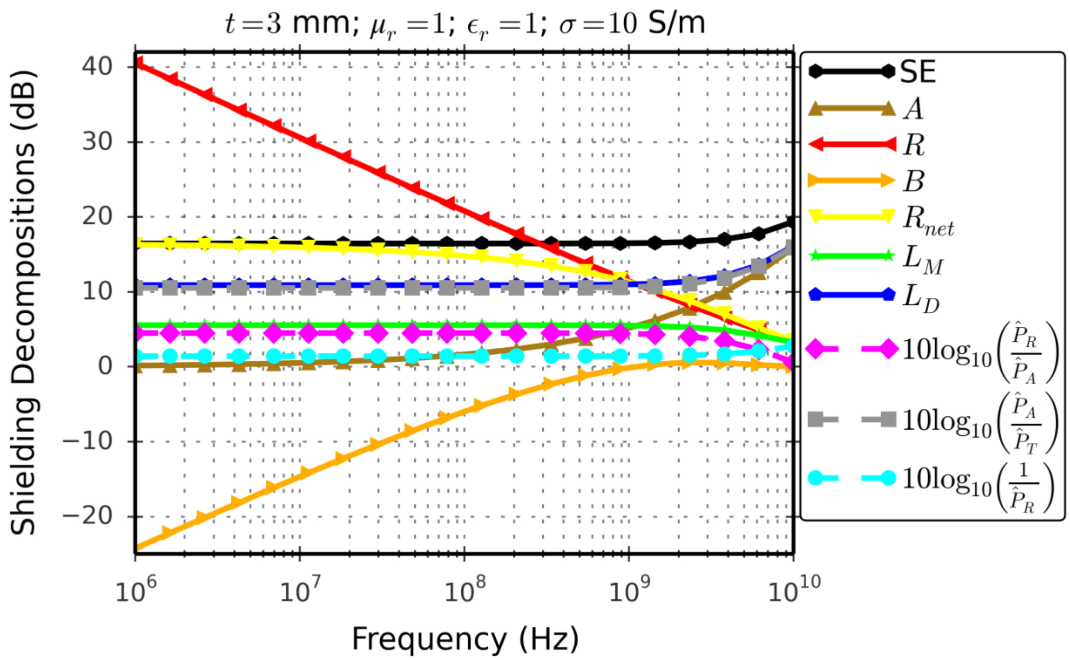

Fig. 6. Shielding decompositions for 3 mm-thick shield with σ = 10 S/m.

6. Conclusion

For many applications of shielding materials, it is useful to consider the reflection and absorption contributions to the overall EMSE. The terms in the Schelkunoff decomposition represent intermediate terms in the calculation of EMSE using the transmission line model of shielding. However, these terms are distantly related to measurable quantities and as such are generally poor figures of merit for comparing the reflection and absorption contributions to the shielding effectiveness of materials in experimental situations.

The mismatch decomposition has several advantages compared to the Schelkunoff decomposition. It has only two components that are easily expressed in terms of the amounts of power reflected and absorbed by the shielding material. Additionally, the power absorbed by a shield will go down if that shield becomes a better reflector. Thus it makes sense to quantify the ability of a shield to absorb power by comparing the absorbed power to the power that is not reflected as the mismatch decomposition does. The mismatch loss is also physically meaningful in that can also be interpreted as a comparison loss (comparing the attenuation in a situation of conjugate matching to the actual attenuation). Likewise the terms of the mismatch decomposition can easily be expressed in terms of the constitutive parameters and thickness of the material.

Due to the multitude of definitions for the terms “absorption loss” and “reflection loss” that appear in the literature, the terms in the Schelkunoff decomposition are often misinterpreted. It is important to recognize that the penetration loss and reflection loss of the Schelkunoff decomposition are not related to the normalized absorbed and reflected power in a straightforward or intuitive manner. As was illustrated by the examples in the previous section, the penetration loss can exceed the net reflection loss when the reflected power is around ten-thousand times greater than the absorbed power as in the case of the copper shield example, or when the reflected power is only slightly greater than the absorbed power as in the case of the 10 S/m shield example.

For describing the absorption and contributions to shielding, the figures of merit should convey information that is of interest in practical situations. The terms of the Schelkunoff decomposition are useful for giving an intuitive understanding of the parametric dependence of EMSE, but they otherwise do not convey very useful information. The mismatch decomposition does convey useful information directly related to the reflected and absorbed power, but it should not be mistaken for an approximation of the terms of the Schelkunoff decomposition when the internal reflections correction term is negligible. EMSE can also be decomposed in other manners that may give measures of interest. The examples section of this paper demonstrated how EMSE could be decomposed into three decibel terms representing useful power ratios. In many experimental situations, however, it may be best to use unambiguous figures of merit like the reflectance and absorptance to describe the mechanisms of shielding rather than decibel quantities that add to give the EMSE.

Appendix: Image Parameters and Schelkunoff Decomposition

Image parameters were first defined by Zobel [51] and can be used to completely characterize a reciprocal two-port network with two complex-valued image impedances and a complex-valued image propagation constant. Image parameters will be defined in terms of the ABCD transmission matrix from network theory. The ABCD matrix of the transmission line analogy of a single-layered shield can be expressed as,

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} E_2 \\ H_2 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma t) & \eta \sinh(\gamma t) \\ \frac{1}{\eta}\sinh(\gamma t) & \cosh(\gamma t) \end{bmatrix} \begin{bmatrix} E_2 \\ H_2 \end{bmatrix}. \tag{43}$$

The field quantities in (43) correspond to using the positive x-axis in Fig. 1 as the reference direction for the electric field and the positive y-axis as the reference direction for the magnetic field. The field quantities in (43) can thus be expressed in terms of the quantities defined for the shielding problem as: $E_1 = E_I + E_R$, $H_1 = H_I - H_R = (E_I - E_R)/\eta_0$, $E_2 = E_T$, and $H_2 = H_T = E_T/\eta_0$. The ABCD matrix has a unity determinant for a reciprocal two-port network and satisfies $A = D$ for a symmetric two-port network.

The image impedances of a reciprocal two-port network can be expressed as

$$\left(Z_{m1}, Z_{m2}\right) = \left(\sqrt{\frac{AB}{CD}}, \sqrt{\frac{BD}{AC}}\right). \tag{44}$$

A network with the source and load impedances equal to the respective image impedances of the network is said to be image matched and the impedance looking in the forward and backward directions is the same at both the input and output terminals. The image propagation constant of a reciprocal two-port network can be expressed as:

$$\gamma_m = \alpha_m + j\beta_m = \cosh^{-1}\sqrt{AD}\,. \tag{45}$$

Note that the two image impedances reduce to η and the image propagation constant reduces to γt for the ABCD matrix of the single layer shield in (43).

A decomposition of insertion loss very similar to the Schelkunoff decomposition of shielding, but using image parameters, is applied to circuit filters in [51], [52]. This decomposition can be derived by hypothetically considering ideal transformers with complex-valued ratios placed on either end of the network providing conversion from the actual source and load impedances to the image impedances of the network [53]. Adaption of this concept to the transmission line analogy of shielding to provide a generalization of the Schelkunoff decomposition is presented below.

From the image impedances defined above, we can define terms analogous to reflection coefficients as follows:

$$\begin{aligned}\rho_{m1} &= \left(Z_{m1}-\eta_0\right)/\left(Z_{m1}+\eta_0\right)\\ \rho_{m2} &= \left(Z_{m2}-\eta_0\right)/\left(Z_{m2}+\eta_0\right)\end{aligned}. \quad (46)$$

Likewise, we can define terms analogous to transmission coefficients as follows:

$$\begin{aligned}T_{m1} &= \left(2\sqrt{Z_{m1}\eta_0}\right)/\left(Z_{m1}+\eta_0\right)\\ T_{m2} &= \left(2\sqrt{Z_{m2}\eta_0}\right)/\left(Z_{m2}+\eta_0\right)\end{aligned}. \quad (47)$$

Note that these image transmission and reflection coefficients are defined for waves traveling into the network from both sides, which is different than the analogous definitions used in Fig. 1 (in which case both transmission coefficients are for a wave traveling in the positive *z* direction). Then the EMSE can be expressed as,

$$SE = A_m + R_m + B_m, \quad (48)$$

where, the image absorption loss is,

$$A_m = -20\log_{10}\left|e^{-\gamma_m}\right| = 8.686\alpha_m, \quad (49)$$

the image reflection loss is,

$$R_m = -20\log_{10}\left|T_{m1}T_{m2}\right|, \text{ and} \quad (50)$$

the image interaction loss is,

$$B_m = 20\log_{10}\left|1-\rho_{m1}\rho_{m2}e^{-2\gamma_m}\right|. \quad (51)$$

Likewise, we will call the following term the image net reflection loss:

$$R_{m,net} = R_m + B_m. \quad (52)$$

For a symmetric shield (i.e. $S_{11} = S_{22}$), the image reflection coefficient and the image propagation constant are equal to the corresponding terms that would be found by using the method presented in Section 3.1. Thus, for a symmetric shield, converting the shield's scattering matrix to its ABCD matrix representation and then solving for the image absorption loss, image reflection loss, and image interaction loss is equivalent to obtaining the penetration loss, reflection loss, and internal reflections correction terms, respectively, of the Schelkunoff decomposition from scattering parameters using the method presented in Section 3.1.

References

[1] P. F. Wilson, M. T. Ma, and J. W. Adams, "Techniques for Measuring the Electromagnetic Shielding Effectiveness of Materials : Part I: Far-field Source Simulation," *IEEE Trans. Electromag. Compat.*, vol. 30, no. 3, pp. 239–250, 1988.

[2] B. Hornbostel, U. Leute, P. Pötschke, J. Kotz, D. Kornfeld, P.-W. Chiu, and S. Roth, "Attenuation of electromagnetic waves by carbon nanotube composites," *Phys. E Low-dimensional Syst. Nanostructures*, vol. 40, no. 7, pp. 2425–2429, May 2008.

[3] A. Saib, L. Bednarz, R. Daussin, C. Bailly, J.-M. Thomassin, C. Pagnoulle, C. Detrembleur, R. Jerome, and I. Huynen, "Carbon nanotube composites for broadband microwave absorbing materials," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 6, pp. 2745–2754, Jun. 2006.

[4] K. Ehinger, S. Summerfield, W. Bauhofer, and S. Roth, "DC and microwave conductivity of iodine-doped polyacetylene," *J. Phys. C Solid State Phys.*, vol. 17, pp. 3753–3762, 1984.

[5] H. Tong, G. Zhu, and W. Mao, "Development of EMI shielding materials characterized by low secondary electromagnetic radiation pollution," in *2011 Second International Conference on Mechanic Automation and Control Engineering*, 2011, pp. 2075–2077.

[6] B. S. Villacorta, A. A. Ogale, and T. H. Hubing, "Effect of Heat Treatment of Carbon Nanofibers on the Electromagnetic Shielding Effectiveness of Linear Low Density Polyethylene Nanocomposites," *Polym. Eng. Sci.*, vol. 53, no. 2, pp. 417–423, 2013.

[7] W. Chiang and Y. Chiang, "Effect of Titanate Coupling Agent on Electromagnetic Interference Shielding Effectiveness and Mechanical Properties of PC-ABS-NCF Composite," *J. Appl. Polym. Sci.*, vol. 46, pp. 673–681, 1992.

[8] K. R. Paton and A. H. Windle, "Efficient microwave energy absorption by carbon nanotubes," *Carbon N. Y.*, vol. 46, no. 14, pp. 1935–1941, Nov. 2008.

[9] A. S. Hoang, "Electrical conductivity and electromagnetic interference shielding characteristics of multiwalled carbon nanotube filled polyurethane composite films," *Adv. Nat. Sci. Nanosci. Nanotechnol.*, vol. 2, no. 2, p. 025007, May 2011.

[10] B. Fugetsu, E. Sano, M. Sunada, Y. Sambongi, T. Shibuya, X. Wang, and T. Hiraki, "Electrical conductivity and electromagnetic interference shielding efficiency of carbon nanotube/cellulose composite paper," *Carbon N. Y.*, vol. 46, no. 9, pp. 1256–1258, Aug. 2008.

[11] D. D. . Chung, "Electromagnetic interference shielding effectiveness of carbon materials," *Carbon N. Y.*, vol. 39, no. 2, pp. 279–285, Feb. 2001.

[12] N. F. Colaneri and L. W. Shacklette, "EMI Shielding Measurements of Conductive Polymer Blends," *IEEE Trans. Instrum. Meas.*, vol. 41, no. 2, pp. 291–297, 1992.

[13] J.-C. Huang, "EMI Shielding Plastics : A Review," *Adv. Polym. Technol.*, vol. 14, no. 2, pp. 137–150, 1995.

[14] D. D. . Chung, "Materials for Electromagnetic Interference Shielding," *J. Mater. Eng. Perform.*, vol. 9, no. 3, pp. 350–354, 2000.

[15] Y. Yang, M. C. Gupta, K. L. Dudley, and R. W. Lawrence, "Novel carbon nanotube-polystyrene foam composites for electromagnetic interference shielding.," *Nano Lett.*, vol. 5, no. 11, pp. 2131–4, Nov. 2005.

[16] C. Chen and K. Naishadham, "Plane Wave Shielding Effectiveness Of Conductive Polymer Films," in *Proceedings of IEEE 1990 Southeastcon*, 1990, pp. 38–41.

[17] M. Lin and C. H. Chen, "Plane-Wave Shielding Characteristics of Anisotropic Laminated Composites," *IEEE Trans. Electromag. Compat.*, vol. 35, no. 1, pp. 21–27, 1993.

[18] K. Naishadham, “Shielding effectiveness of conductive polymers,” *IEEE Trans. Electromagn. Compat.*, vol. 34, no. 1, pp. 47–50, 1992.

[19] W.-S. Jou, H.-Z. Cheng, and C.-F. Hsu, “The electromagnetic shielding effectiveness of carbon nanotubes polymer composites,” *J. Alloys Compd.*, vol. 434–435, pp. 641–645, May 2007.

[20] P. Saini and M. Arora, “Microwave Absorption and EMI Shielding Behavior of Nanocomposites Based on Intrinsically Conducting Polymers, Graphene and Carbon Nanotubes,” in *New Polymers for Special Applications*, InTech, 2012, pp. 71–111.

[21] P. Saini, V. Choudhary, B. P. Singh, R. B. Mathur, and S. K. Dhawan, “Enhanced microwave absorption behavior of polyaniline-CNT/polystyrene blend in 12.4–18.0GHz range,” *Synth. Met.*, vol. 161, no. 15–16, pp. 1522–1526, Aug. 2011.

[22] a. N. Yusoff, M. H. Abdullah, S. H. Ahmad, S. F. Jusoh, a. a. Mansor, and S. a. a. Hamid, “Electromagnetic and absorption properties of some microwave absorbers,” *J. Appl. Phys.*, vol. 92, no. 2, p. 876, 2002.

[23] K. L. Kaiser, *Electromagnetic Compatibiltity Handbook*. Boca Raton: CRC Press, 2004.

[24] H. Ott, *Noise Reduction Techniques in Electronic Systems*, 2nd ed. New York: John Wiley & Sons, Inc., 1988.

[25] T. Williams, *EMC for Product Designers*, 4th ed. Newnes, 2007.

[26] C. R. Paul, *Introduction to Electromagnetic Compatibility*, 2nd ed. John Wiley & Sons, Inc., 2006.

[27] R. Perez, Ed., *Handbook of Electromagnetic Compatibility*. Academic Press, 1995.

[28] S. Celozzi, R. Araneo, and G. Lovat, *Electromagnetic Shielding*. John Wiley & Sons, Inc., 2008.

[29] S. A. Schelkunoff, “The Electromagnetic Theory of Coaxial Transmission Lines and Cylindrical Shields,” *Bell Syst. Tech. J.*, vol. 13, no. 4, pp. 532–579, Oct. 1934.

[30] S. A. Schelkunoff, *Electromagnetic Waves*. Van Nordstrum, 1943.

[31] S. A. Schelkunoff, “The Impedance Concept and its Application to Problems of Reflection, Refraction, Shielding and Power Absorption,” *Bell Syst. Tech. Journal1*, vol. 17, no. 1, 1938.

[32] P. F. Keebler, K. O. Phipps, and F. A. Name, “Shielding effectiveness with a twist,” in *2008 IEEE International Symposium on Electromagnetic Compatibility*, 2008, pp. 1–6.

[33] A. C. D. Whitehouse, “Screening: new wave impedance for the transmission-line analogy,” *Proc. Inst. Electr. Eng.*, vol. 116, no. 7, p. 1159, 1969.

[34] D. R. Brush, R. B. Schulz, G. C. Huang, W. L. Williams, V. C. Plantz, and L. Jorgensen, “Comparison of Shielding Calculations,” *IEEE Trans. Electromagn. Compat.*, vol. EMC-10, no. 1, pp. 175–177, 1968.

[35] I. Youngs, “The Shielding Effectiveness of Composite Media - a Parametric Analysis Supporting an Engineering Perspective,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 5, pp. 1145–1153, Oct. 2007.

[36] K. M. Lim, M. C. Kim, K. A. Lee, and C. G. Park, “Electromagnetic wave absorption properties of amorphous alloy-ferrite-epoxy composites in quasi-microwave band,” *IEEE Trans. Magn.*, vol. 39, no. 3, pp. 1836–1841, May 2003.

[37] P. B. Jana, A. K. Mallick, S. K. De, and M. Used, "Effects of sample thickness and fiber aspect ratio on EMI shielding effectiveness of carbon fiber filled polychloroprene composites in the X-band frequency range," *IEEE Trans. Electromagn. Compat.*, vol. 34, no. 4, pp. 478–481, 1992.

[38] Z. Liu, G. Bai, Y. Huang, Y. Ma, F. Du, F. Li, T. Guo, and Y. Chen, "Reflection and absorption contributions to the electromagnetic interference shielding of single-walled carbon nanotube/polyurethane composites," *Carbon N. Y.*, vol. 45, no. 4, pp. 821–827, Apr. 2007.

[39] N. Li, Y. Huang, F. Du, X. He, X. Lin, H. Gao, Y. Ma, F. Li, Y. Chen, and P. C. Eklund, "Electromagnetic interference (EMI) shielding of single-walled carbon nanotube epoxy composites.," *Nano Lett.*, vol. 6, no. 6, pp. 1141–5, Jun. 2006.

[40] M. H. Al-Saleh and U. Sundararaj, "Electromagnetic interference shielding mechanisms of CNT/polymer composites," *Carbon N. Y.*, vol. 47, no. 7, pp. 1738–1746, Jun. 2009.

[41] M. H. Al-Saleh and U. Sundararaj, "X-band EMI shielding mechanisms and shielding effectiveness of high structure carbon black/polypropylene composites," *J. Phys. D. Appl. Phys.*, vol. 46, no. 3, Jan. 2013.

[42] A. Ameli, P. U. Jung, and C. B. Park, "Electrical properties and electromagnetic interference shielding effectiveness of polypropylene/carbon fiber composite foams," *Carbon N. Y.*, vol. 60, pp. 379–391, Aug. 2013.

[43] Y. K. Hong, C. Y. Lee, C. K. Jeong, D. E. Lee, K. Kim, and J. Joo, "Method and apparatus to measure electromagnetic interference shielding efficiency and its shielding characteristics in broadband frequency ranges," *Rev. Sci. Instrum.*, vol. 74, no. 2, p. 1098, 2003.

[44] H. M. Kim, K. Kim, C. Y. Lee, J. Joo, S. J. Cho, H. S. Yoon, D. A. Pejaković, J. W. Yoo, and A. J. Epstein, "Electrical conductivity and electromagnetic interference shielding of multiwalled carbon nanotube composites containing Fe catalyst," *Appl. Phys. Lett.*, vol. 84, no. 4, p. 589, 2004.

[45] P. Saini, V. Choudhary, B. P. Singh, R. B. Mathur, and S. K. Dhawan, "Polyaniline–MWCNT nanocomposites for microwave absorption and EMI shielding," *Mater. Chem. Phys.*, vol. 113, no. 2–3, pp. 919–926, Feb. 2009.

[46] W. B. Weir, "Automatic Measurement of Complex Dielectric Constant and Permeability," *Proc. IEEE*, vol. 62, no. 1, pp. 33–36, 1974.

[47] R. B. Schulz, V. C. Plantz, and D. R. Brush, "Shielding theory and practice," *IEEE Trans. Electromagn. Compat.*, vol. 30, no. 3, pp. 187–201, 1988.

[48] R. W. Beatty, "Insertion Loss Concepts," *Proc. IEEE*, 1964.

[49] K. A. Norton, "Should the conventional definition of mismatch loss be abandoned?," *Proc. IEEE*, vol. 52, no. 6, pp. 710–710, 1964.

[50] I. T. and T. Corporation, *Reference Data for Radio Engineers*, 4th ed. New York, 1956.

[51] O. J. Zobel, "Transmission Characteristics of Electric Wave-Filters," *Bell Syst. Tech. J.*, vol. 3, no. 4, 1924.

[52] A. T. Starr, *Electric Circuits and Wave Filters*, 2nd ed. London: Sir Isaac Pitman & Sons, Ltd., 1938.

[53] V. Belevitch, *Classical Network Theory*. San Francisco: Holden-Day, 1968.